

Autonomous Above-Water Radiance Measurements from an Offshore Platform: A Field Assessment Experiment

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ABSTRACT

An autonomous system for making above-water radiance measurements has been produced by adding a new measurement scenario to a CIMEL CE-318 sun photometer. The new system, called the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Photometer Revision for Incident Surface Measurement (SeaPRISM), combines the normal CE-318 capability for measuring direct sun irradiance and sky radiance, with a new capability for measuring above-water radiance for the retrieval of water-leaving radiance. The system has been extensively tested during several measurement periods over a 1-yr time frame from August 1999 to July 2000 under various sun elevations along with different atmospheric, seawater, and sea-state conditions. The field assessment of the new instrument was conducted at an oceanographic tower located in the northern Adriatic Sea within the framework of measurement campaigns aimed at supporting ocean color calibration and validation activities. Sample data at 440, 500, 670, 870, and 1020 nm were collected at azimuth and zenith angles satisfying the SeaWiFS Ocean Optics Protocols (and successive revisions) for above-water radiance measurements. Specifically, data were collected with azimuth angles of 90° with respect to the sun plane, and with nadir viewing angles of 30°, 40°, and 45° for above-water measurements and of 150°, 140°, and 135° for sky radiance measurements, respectively (the latter are needed for glint correction of the data). The intercomparison between water-leaving radiances computed from SeaPRISM measurements and those obtained from in-water optical profiles taken with the Wire-Stabilized Profiling Environmental Radiometer (WiSPER) system were performed using 113 coincident sets of measurements collected during clear-sky conditions. The SeaPRISM measurements taken at 40° and corrected for glint effects using different methods show the best agreement with WiSPER data. The intercomparisons exhibit average absolute unbiased percent differences, generally lower than 10% at 440 and 500 nm, and lower than 26% at 670 nm. The intercomparison of the water-leaving radiance ratio $L_w(440)/L_w(500)$ from SeaPRISM data taken at 40° and WiSPER data exhibits average absolute unbiased percent differences lower than 5.6%.

1. Introduction

Water-leaving radiance at wavelength λ in the visible and near-infrared parts of the solar spectrum, $L_w(\lambda)$, is the primary parameter for vicariously calibrating ocean color satellite sensors and for validating the algorithms used for estimating chlorophyll *a* concentration (Hooker and McClain 2000). Most spaceborne instruments, like the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), ensure global products on a routine basis, so extensive spatial and temporal measurements of water-leaving radiance are required to satisfy the calibration and validation objectives (McClain et al. 1998).

Oceanographic cruises can ensure the collection of in-water optical profiles over large areas regardless of the water type, but they can only provide data in a restricted time frame (i.e., from days to weeks). Although shading from the deployment platform can be easily avoided through the use of free-falling profilers that can be floated away from the ship, platform stability is still required for solar reference measurements or for water-leaving radiance measurements through above-water methods. The latter feature is particularly important in the coastal environment, because small research vessels are frequently used for nearshore surveys.

In-water moored systems based on buoys, are an alternative platform when the collection of optical data at discrete depths with very good temporal resolution is needed (Clark et al. 1997). The use of moorings is best suited to clear-water regions, so biofouling effects on the submerged optical surfaces are minimized. The negative influence of waves and currents on the pointing stability of the sensors with respect to the vertical, and on the geometric alignment of the sensors with respect to the sun, must be quantified (i.e., the sensors need to be vertically oriented and outside the shadow of the buoy during data collection). Additional difficulty is the extrapolation of the subsurface upward radiance from discrete measurements taken at a few depths. This process can be significantly influenced by different seawater optical properties (e.g., caused by vertical stratification) within the depth intervals defined by the relative locations of each underwater sensor. Taken together, these elements make moored systems a difficult platform for calibration and validation activities in coastal waters, because the biofouling problem is severe, and the sea state and current structure is a strong function of daily and seasonal forcing.

5. Summary and conclusions

The intercomparison of SeaPRISM (above-water) and WiSPER (in-water) $L_w(\lambda)$ data, highlights the difficulty in minimizing glint effects in above-water radiance measurements collected during clear-sky conditions. The methods discussed in this study for the retrieval of $L_w(\lambda)$ from above-water measurements are based on the removal of sun- and sky-glint effects applying a theoretical sea surface reflectance factor $\rho(\theta)$ and three different processing schemes: (i) making use of time-averaged data (method S95_a); (ii) using the minimum value from a sequence of $L_T(\lambda, \theta, \phi)$ measurements as further minimization of sun-glint effects (method S95_m); and (iii) using time-averaged data and direct sun irradiance measurements to estimate sun-glint residuals (method S00). Recognizing that the small number of measurements collected during each SeaPRISM sea-viewing measurement sequence (three) reduces the statistical robustness of the $L_w(\lambda)$ estimates, the intercomparisons nevertheless demonstrate that with $\phi = \phi_0 + 90^\circ$, the S95_m method at $\theta = 40^\circ$ for spectral averages give the best agreement with WiSPER data.

For the 113 matchups composing the assessment dataset, the S95_m method exhibits $|\psi|$ values of 6.1%, 7.1%, and 20.5% at 440, 500, and 670 nm, respectively. The larger $|\psi|$ values at 670 nm, systematically observed for all the applied processing methods and at all values of θ , is justified by the large surface perturbations induced in the above-water measurement in the red part of the spectrum. It is important to remember the data were taken with different solar positions as well as different atmospheric and marine conditions over a 1-yr period—so the variance associated with seasonal forcing is present in the results—but all measurements were made during clear-sky conditions and for wind speed generally less than 5 m s^{-1} , that is, in near-ideal conditions. The latter would not be expected for fully operational measurements, and sampling issues raised by other investigators for above-water methods in the coastal environment (e.g., high wind speeds) would have to be considered (Toole et al. 2000).

The intercomparison of radiance ratios $L_w(440)/L_w(500)$ from SeaPRISM and WiSPER data have $|\psi|$ values ranging from 4.5% to 5.6% at $\theta = 40^\circ$, with the best result derived from the S95_a and S00 methods. The latter is an important accomplishment, in terms of using SeaPRISM for remote sensing calibration and validation activities, because it is close to the 5% SeaWiFS radiometric objectives. It is important to note the S95_m method applied for radiance ratios is sufficiently close to the 5% level at $\theta = 40^\circ$ that additional investigations into the sources of variances might render this method acceptable as well.

The analysis of the uncertainty budget (restricted to instrument overall intercalibration accuracy, tower- and self-shading, and environmental perturbations), shows a quadrature sum of the relative uncertainties generally within 4%–5% for both SeaPRISM and WiSPER radiances, with the exception of the SeaPRISM water-leaving radiance at 670 nm exceeding 12% (Table 4). The latter high value is again justified by the significant contribution of surface effects in the red part of the spectrum

and is in agreement with the data shown in Table 2. This level of uncertainty accounts for approximately half of the spectral differences for the S95_m method, and it is close to the band ratio differences. The former suggests some additional sources of uncertainty have not been well quantified (e.g., bidirectional effects in the spatial distribution of the in-water radiance field, differences in the above- and in-water tower perturbations, etc.), while the latter suggests that some uncertainties are cancelled or minimized by the band ratio calculation (Hooker et al. 2002).

Based on the results achieved with the SeaPRISM prototype system, the requirements for an operational, fully autonomous system can be considered:

- 1) a maximum number of channels, at the appropriate center wavelengths, for ocean color observations (IOCCG 1998) are needed;
- 2) programmable θ and ϕ angles to satisfy the testing or operational use of different measurement protocols;
- 3) the collection of a maximum number of sea-viewing values (per measurement sequence and per channel), to ensure statistical robustness for rejecting measurements contaminated by wave, cloud, and sun-glint effects and to maximize the signal-to-noise ratio;
- 4) characterization of the instrument offset during each measurement sequence; and
- 5) automatic data transmission through a satellite link.

There are a few restrictions with these recommendations if SeaPRISM instruments are to be used within the AERONET activity. First, AERONET requires at least six channels in keeping with WMO recommendations for aerosol and water vapor sun photometry (Frohlich and London 1986), so this leaves two channels for ocean color applications (in addition to the channels within the six for sun photometry that are useful for ocean color work). Given the present form of operational ocean color algorithms (O'Reilly et al. 1998), 443, 490, 510, and 555 nm are appropriate wavelengths to consider. Second, the amount of data that can be transmitted through the satellite link is limited, so to maximize the number of sea-viewing measurements (under most circumstances 11 should be possible), some of the data processing could be handled by the sun photometer control unit. Third, the SeaPRISM system does not include a capability for making $E_d(0^+, \lambda)$ measurements, which are needed for the computation of normalized water-leaving radiances (Gordon and Clark 1981). For the validation of satellite radiometric data and the vicarious calibration of space sensors; however, $L_w(\lambda)$ data collected at a time very close to the satellite overpass, may be used without any normalization. Different applications requiring normalized water-leaving radiances could use, during clear sky conditions, the aerosol optical thickness retrieved from the direct sun irradiance measurement and the aerosol scattering phase function derived from the sky radiance measurement as input for a theoretical computation of $E_d(0^+, \lambda)$.